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Investigation on the Performance Characteristics of Two Valveless Pulse Jets Operating in Phase Opposition

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INVESTIGATION ON THE PERFORMANCE CHARACTERISTICS OF TWO VALVELESS PULSE JETS OPERATING IN PHASE OPPOSITION

by

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This thesis submitted by Donald A. Moen in partial fulfillment of the requirements for the Degree of Master of Science in the University of North Dakota is hereby approved by the Committee under whom the work has been done.

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ABSTRACT

INVESTIGATION ON THE PERFORMANCE CHARACTERISTICS OF TWO VALVELESS PULSE JETS OPERATING IN PHASE OPPOSITION

This investigation was suggested by an earlier investigation done on a single valveless pulse jet engine at the University of North Dakota by Roger W. Engebretson. It was thought that if two of these engines could be coupled in such a manner that they would fire alternately, the performance per engine could be improved. A literature search indicated that, while valved pulse jets had been successfully operated in the described manner, no one had previously operated two valveless pulse jet engines in phase opposition.

The objective of this project was to design a device for coupling two of these engines as prescribed above and to investigate the performance characteristics of the coupled engines.

As a result of this project, two valveless pulse jet engines have been successfully operated in a coupled manner and through the use of high speed photography, it was established that the engines were firing alternately. The total thrust per engine and the total-thrust specific fuel consumption for the coupled engines were inferior to the respective values for Engebretson's single engine. However, indications are that the coupled engines have a potential for improvement through further research. In the thesis, six suggestions for further research projects are advanced.

CHAPTER I

INTRODUCTION

Pulsating combustion engines have long been of interest as a propulsive device because of their inherent mechanical simplicity. However, the development of the pulsating combustion engine has been retarded by low thermal efficiency, high noise levels, and in some cases, fatigue of mechanical valves.

In general, pulsating combustion engines can be classified as being one of two types - the valved pulse jet engine or the valveless pulse jet engine. Basically the valved pulse jet engine has only one moving part, a mechanical valve which controls the air flow to the engine. In the valveless pulse jet, however, even the one moving part has been eliminated to produce a prime mover with no moving parts. Actually, the term "valveless" pulse jet is somewhat misleading since all pulse jets must have valves. In the valveless pulse jet, the mechanical valve has been replaced by a no-moving-parts aerodynamic valve.

To date, the valved pulse jet has enjoyed the greatest number of practical applications since, at the current state of pulse jet development, the thermal efficiency of the valved units appears to be higher. Applications of the valved pulse jet include jet-powered helicopters (1,2) and the infamous German V-1 buzz bomb of World War II (3). However, the valved pulse jet has a serious disadvantage in that the mechanical valves are subject to fatigue and must be frequently replaced (4). Thus, if the thermal efficiency of the valveless pulse jet could be improved, it would seem that this engine should excel since it represents the ultimate in mechanical simplicity - no moving parts.

The valveless pulse jet is certainly not a new device. The first known engine of this type was constructed by Marconnet in 1909 (5,6). Even prior to this date, experiments involving pulsating combustion were performed by Holzworth in 1905 (7) and Karavodine in 1908 (8).

Although the valveless pulse jet seems to have a potential for development, France is apparently the only country where any large-scale development effort has been made. Under the sponsorship of S.N.E.C.M.A.[1] the French have developed the valveless pulse jet to the point where it has been used to propel light aircraft on an experimental basis (9,10,11,12). Although S.N.E.C.M.A. appears to have made considerable progress in their work on the valveless pulse jet, they seem to be reluctant to publish detailed information about their engines. F. H. Reynst who was once a research engineer for S.N.E.C.M.A. had a lifelong interest in pulsating combustion and his many papers on the subject have been collected and edited by Thring (13). The publication by Thring is considered by this author to be one of the most complete works on pulsating combustion available.

In the United States, the two known locations of current valveless pulse jet research are the University of North Dakota and the University of Illinois. At the University of Illinois, R. W. McCloy has experimented with an improved aerodynamic valve (14,15). McCloy has also done experimental work to establish the appropriate boundary conditions for applying existing theoretical analysis of valved pulse

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[1]S.N.E.C.M.A. - Societe Nationale d'Etude et de Construction de Motours d'Aviation - The French Nationalized Aircraft Company.

jets to the valveless pulse jet engine (16).

Several excellent attempts at theoretical analysis of the pulse jet are available. However, the pulse jet is inherently a non-steady-state device and, consequently, theoretical analyses tend to get complex and difficult to apply (17). With reference to a theoretical method of computing thrust, Schultz-Grunow states that such a method could not be expected since, "The combustion process so completely eludes theoretical treatment that here experimentation alone is decisive." (18). Further, McDonald found that his attempts at theoretical analysis were hampered by lack of really fundamental information on the phenomena of pulsating combustion (19). Consequently, much pulse jet research has proceeded on an empirical basis as is the case at the University of North Dakota.

At the University of North Dakota the valveless pulse jet was first brought to campus by personnel of the Grand Forks Coal Research Laboratory (U. S. Bureau of Mines). Under the direction of project coordinator, R. C. Ellman, L. Dockter and J. W. Belter have been experimenting with a valveless pulse jet engine used to supply high velocity hot gases to a lignite coal dryer (20). Also, this group is largely responsible for stimulating further interest in the device.

In 1964 Roger W. Engebretson undertook an investigation of the valveless pulse jet as a propulsion device (21). Using Belter's experimental work as a background, Engebretson varied certain geometric engine parameters and measured the effect of thrust, specific fuel consumption, frequency, and air-fuel ratio. Although Engebretson was able to make a significant improvement in engine performance by his fine tuning effort, thermal efficiency of his engine was still too low to be of practical value. Also, one of his major problems was the high noise level (130 db.) in the vicinity of the operating engine.

In 1910 Esnault-Pelterie was experimenting with two valved pulse jets which were coupled in such a way as to fire alternately (22). Esnault-Pelterie found that each engine was strengthened by the other so that the pressure amplitudes "became wider" and the noise level was reduced due to acoustic wave destructive interference. Although Esnault-Pelterie apparently achieved a degree of success with his coupled engines, no record could be found of anyone attempting to couple valveless pulse jets in a similar manner. Hence, the present project evolved in which two valveless pulse jets were coupled in such a manner as to fire alternately.

As implied above, the goals of this project were to design a device which would couple two valveless pulse jets in the prescribed manner, and to investigate the performance characteristics of the coupled engines. In evaluating the performance of the coupled engines, Engebretson's single-engine data could be used for comparison purposes since the individual engines were constructed to be, as nearly as possible, identical to Engebretson's engine.

CHAPTER II

PRINCIPLE OF OPERATION

Several excellent references are available which describe the operation of a single pulse jet tube (23,24,25). However, for the convenience of the reader, a brief description is presented here.

A schematic diagram of the valveless pulse jet is shown in figure 1. It consists fundamentally of an exhaust or resonance tube several feet long and an air inlet pipe. The upstream end of the exhaust tube may or may not be of a larger diameter than the downstream end but, in either case, it forms the combustion chamber. The fuel lines, starting air inlet, and spark plug are all located in this section.

During start-up, a source of fresh air is required to purge the system and to supply sufficient oxygen for initial combustion. Prior to start-up, the starting air and spark plug are both turned on. Then, upon opening the fuel valve suddenly, rapid combustion occurs resulting in a steep pressure rise. Because of the action of the aerodynamic valve, there is a preferential flow of the exhaust gases through the exhaust pipe. However, because the aerodynamic valve is inherently a leaky valve, a portion of the exhaust gases also flow out through the intake pipe. The momentum of the flowing gas columns creates a negative pressure in the combustion chamber which, in turn, halts the outflow of gases and initiates an inflow from both directions. Because the momentum of gases in the exhaust pipe is far greater than the momentum of gases in the intake pipe, the direction of flow is

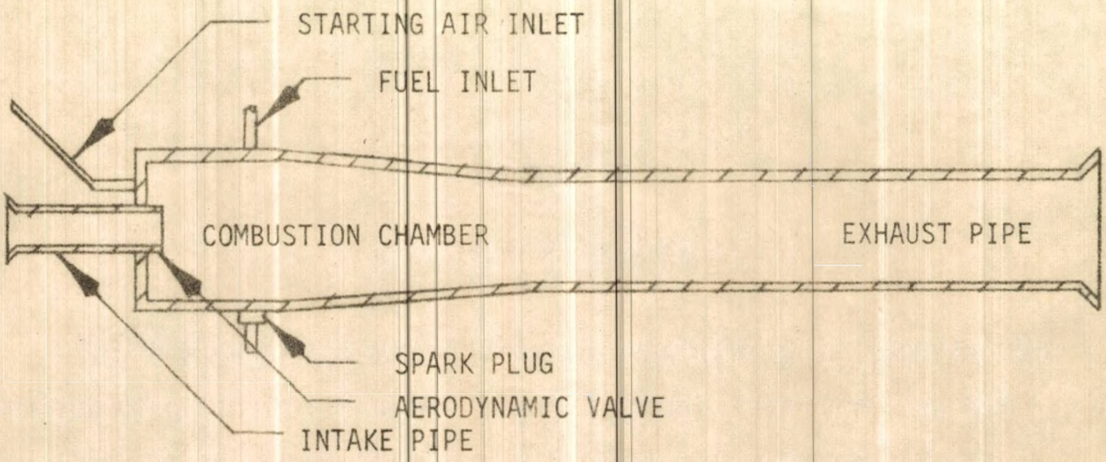


FIGURE 1. SCHEMATIC DIAGRAM

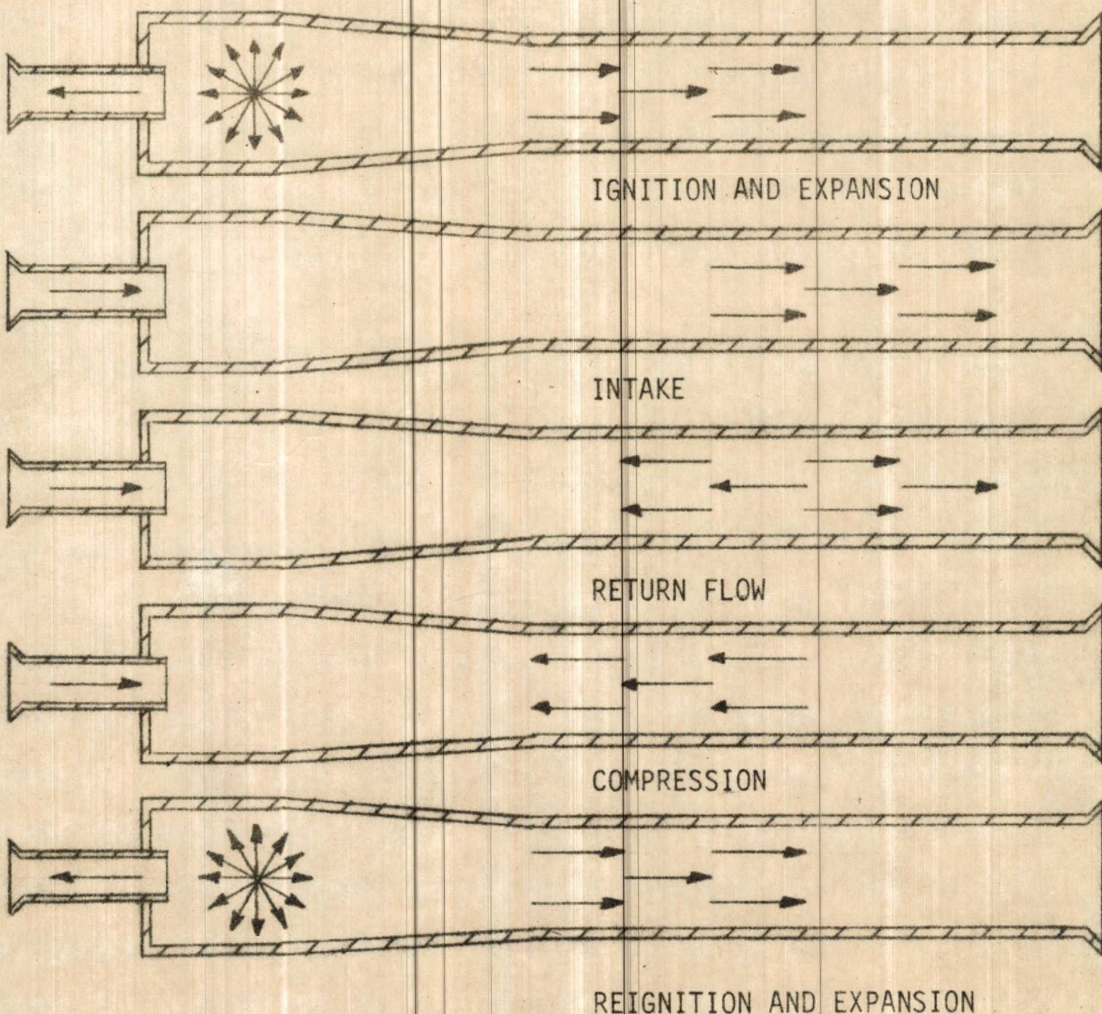


FIGURE 2. COMBUSTION CYCLE

reversed earlier in the intake. The length of the intake pipe is such that the inflow through this passage consists mainly of fresh air which refills the combustion chamber. When the flow in the exhaust pipe does finally reverse, the frontal zone of this inward flowing gas column is hot exhaust gases. This gas column causes a slight compression of the air-fuel mixture (the fuel is flowing continuously) and assists in the spontaneous ignition which starts the next cycle. There is some uncertainty as to the actual mechanism of reignition and different theories exist (26). However, indications are that exhaust backflow does play an important role (27). A graphical illustration of the combustion cycle is given in figure 2. Once the engine is running, starting air and spark are turned off.

The intake pipe may be located either as shown in figure 1 or, within limits, in the sidewall of the combustion chamber (28). The aerodynamic valve may take one of several forms ranging from the simple Borda mouth to the "valvular conduit" patented by Tesla in 1920 (29). In the engines considered here, the Borda mouth was used. The flares shown on the outer ends of the intake and exhaust pipes enhance inflow and were found, by Engebretson, to improve performance.

CHAPTER III

COUPLING THEORY AND DESIGN

As stated in Chapter 1, one objective of this project was to design a device for coupling two valveless pulse jets in such a manner that they fire alternately. In keeping with this objective, two distinct coupling techniques were attempted: intake coupling and exhaust coupling. Although success was achieved only with exhaust coupling, intake coupling was attempted first and, hence, will be discussed first.

During Engebretson's work, he observed what appeared to be a most unique type of flow occurring in the intake pipe (30). It appeared that the outflowing exhaust gases were traveling through the center core of the intake pipe while the air intake was occurring around the periphery as illustrated in figure 3. It was thought that perhaps this unique flow could be utilized to couple the engines in the desired manner. The basic experimental intake coupling arrangement is shown in figure 4.

It was thought that, by aiming the intakes at each other, the exhaust pulse from engine number 1 could be used to cause an aspirating effect in the intake of engine number 2. This effect would serve to increase the mass of air charging engine number 2 and also to time the firing of engine number 2. Likewise, the exhaust pulse from engine number 2 would have a similar effect on engine number 1. The net effect on each engine would be a dynamic charging which would prolong the intake process causing a greater mass of air fuel mixture to be

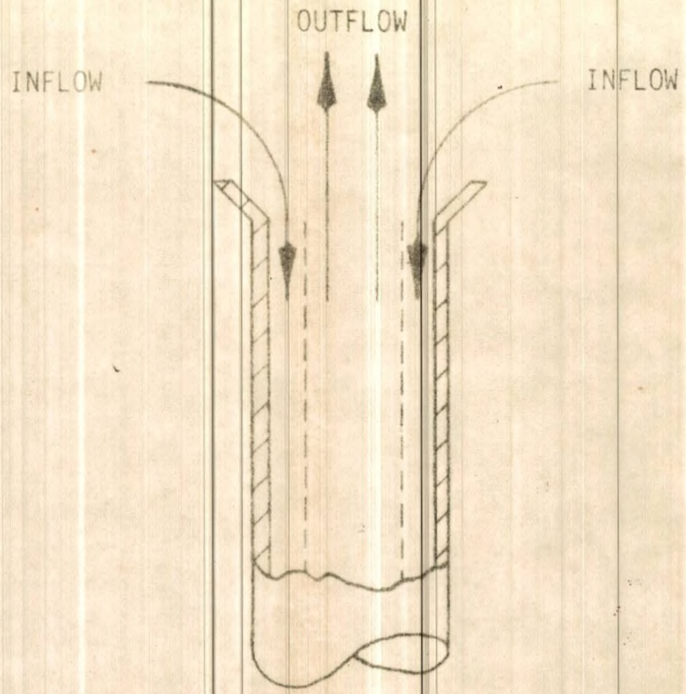


FIGURE 3. SKETCH OF ASSUMED INTAKE ACTION

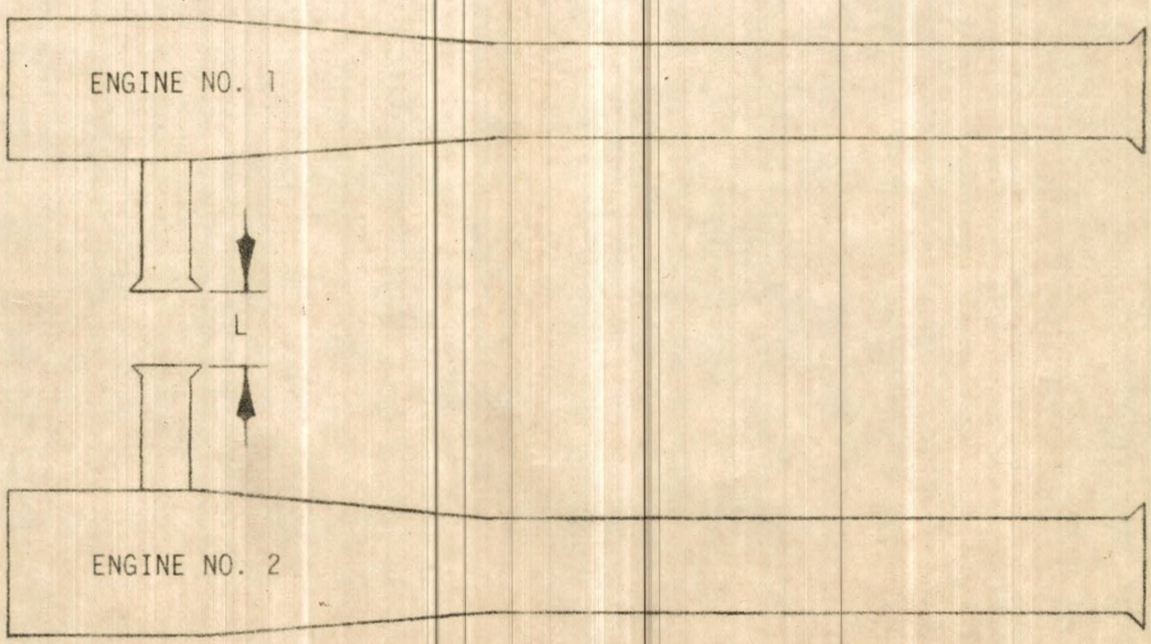


FIGURE 4. SKETCH ILLUSTRATING CONFIGURATION FOR UNSUCCESSFUL INTAKE COUPLING ATTEMPT

burned per cycle and, thus, increasing the thrust. Also, on the basis of Esnault-Pelterie's results, (31) it was anticipated that the noise level should be reduced due to pressure wave destructive interference. This idea for coupling was founded on the hypothesis that the two flows are truly concentric and could be made to remain so in the transfer of exhaust from one intake to the other. Notice that the scheme leaves the exhaust tubes open to the atmosphere. This feature would be desirable since the backflow of fresh air down the exhaust pipes gives the valveless pulse jet a relatively high propulsion efficiency which helps to counteract the low thermal efficiency (32,33). Thermal efficiency can be defined as:

$$\eta_t = \frac{\text{kinetic energy of the exhaust gases}}{\text{energy input}}$$

while propulsion efficiency (for an engine propelling a vehicle) can be defined as:

$$\eta_p = \frac{\text{thrust output}}{\text{power unit output}}$$

Power unit output is the sum of the effective thrust output and the kinetic energy of the thrust stream which is lost (34).

There is no theory and only a minimum of data available to describe the flow in the intake. Since a detailed investigation of this flow was considered to be beyond the scope of the project, the investigation proceeded on a "cut and try" basis.

Two valveless pulse jet engines were oriented as shown in figure 4. In order that comparisons could be made, the engines were constructed so as to be nominally identical to Engebretson's final engine, the dimensions of which are given in figure 5. The engines were run with the configuration of figure 4 with the intake gap, L, being varied from 4 inches to 12 inches at 1-inch intervals. At each intake gap, thrust was determined as a function of fuel flow rate throughout the fuel flow range of the engines. As described below, all evidence indicated that

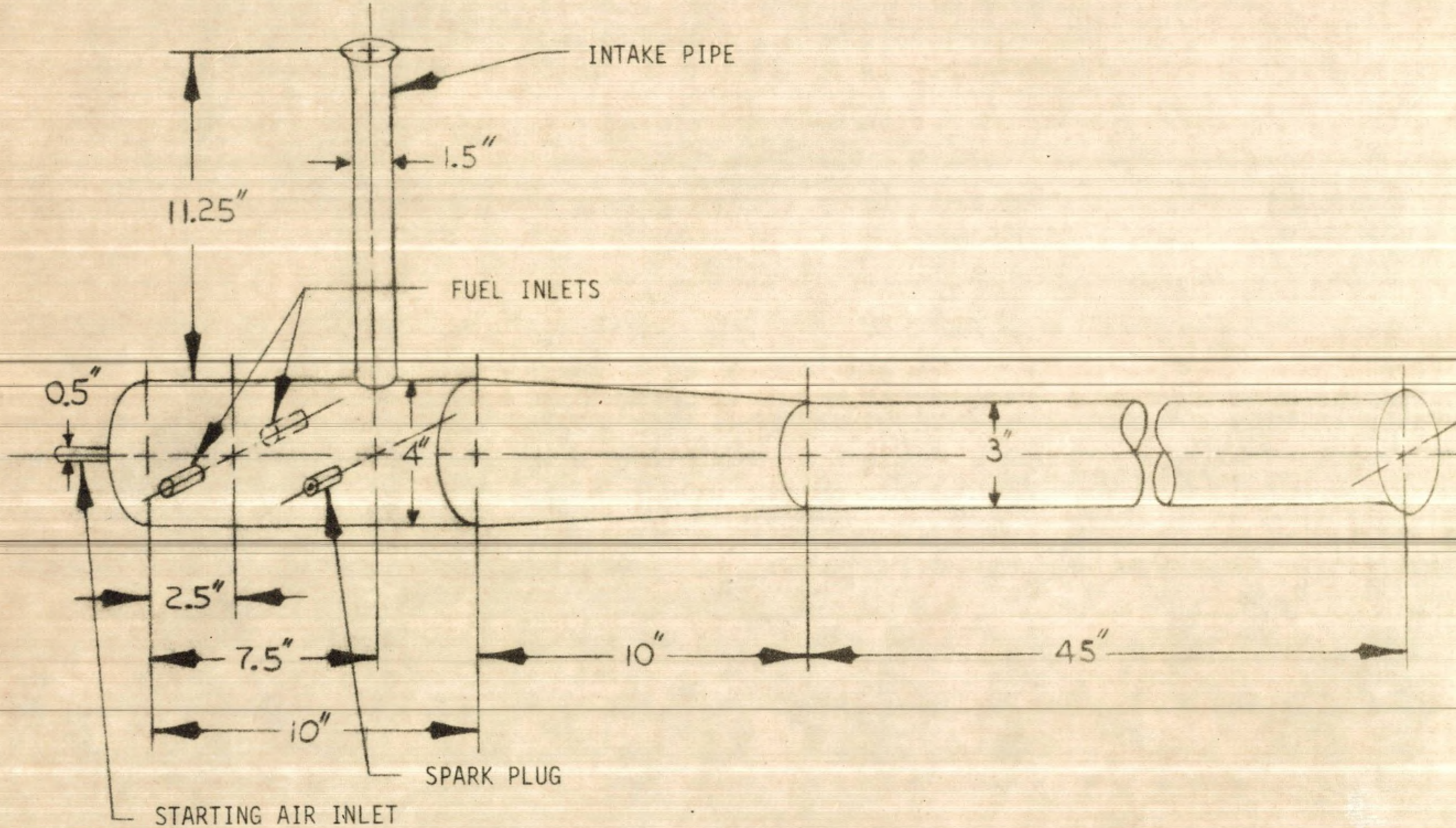


FIGURE 5. SKETCH OF ENGEBRETSON'S SINGLE VALVELESS PULSE JET ENGINE

the engines were not coupling but rather, were interfering with each other.

The maximum thrust obtainable was 3.09 lb_f (1.55 lb_f per engine) which was far inferior to the 6.0 lb_f total thrust or 3.92 lb_f exhaust thrust obtained by Engebretson (35). Further, all thrust data was erratic and could not be duplicated in successive runs. The presence of an audible beat frequency was noted indicating that the engines were operating independently at slightly different frequencies. These beats also showed up as fluctuations in the fuel pressure and thrust, and made the respective measurements difficult. Engine operation was possible over only a limited fuel flow range.

By visual observation of the flames developed at the ends of the intake tubes, it became apparent that the exhaust flow was not remaining concentric but was spreading out to interfere with the intake flow. Several trials at placing geometric shapes in the intakes were made in an attempt to prevent the exhaust interference. These shapes, however, were also unsuccessful and led to the conclusion that coupling the intakes in the above manner was not possible. It seemed that any attempt to modify the intake tubes caused the performance to deteriorate, thus indicating a need for a detailed study of this peculiar flow before further attempts at intake coupling. In retrospect, it is thought that one of the reasons for failure was that the scheme attempted to control a gas column of large momentum (the exhaust pipe) with one of small momentum (the intake pipe). Appendix 1 gives an account of the various geometric shapes tried in intake coupling.

When intake coupling proved unsuccessful, the next step was to try exhaust coupling. Schultz-Grunow (36) did a gas dynamic analysis wherein, through the use of several simplifying assumptions, he was able to describe the operation of a valved pulse jet tube in terms of pressure waves. Although his analysis was for a valved pulse jet, the transition to a valveless pulse jet can be made if new boundary conditions can be established (37). Although a gas dynamic analysis of the valveless pulse jet was considered to be beyond the scope of this project, it was thought that Schultz-Grunow's wave diagrams could be used as a qualitative coupling design guideline. Success seems to verify the assumption.

A simplified version of Schultz-Grunow's wave diagram for a constant diameter pulse jet tube is shown in figure 6. The dimensionless coordinates ξ and τ have been used in place of distance and time respectively where:

$$\xi = \frac{x}{R}$$

$$\tau = \frac{a_1 t}{R}$$

x = distance along the tube measured from the valve

t. = time

R = length of tube

a_1 = speed of sound at atmospheric conditions

Solid lines represent compression waves while broken lines represent rarefaction waves.

Suppose that a pressure rise occurs in the combustion chamber. The pressure rise causes compression wave A to travel to the right while rarefaction wave B travels to the left and is reflected as a rarefaction wave from the closed end of the tube. When compression wave A reaches the open end of the tube, it is reflected as rarefaction wave C. As rarefaction wave C reaches the combustion chamber, the pressure falls and the intake process begins. Rarefaction wave B reflects from the open end of the tube as compression wave D. Compression wave D then proceeds toward the combustion chamber where it stops the intake process and causes a slight compression of the charge.

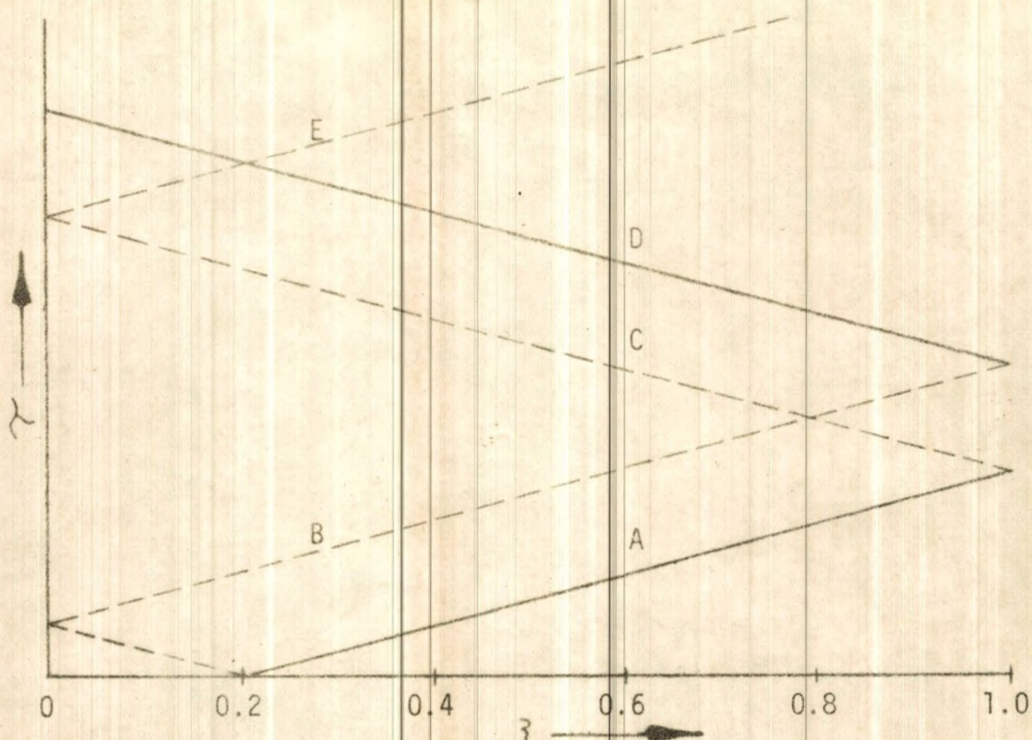


FIGURE 6. SKETCH OF WAVE DIAGRAM

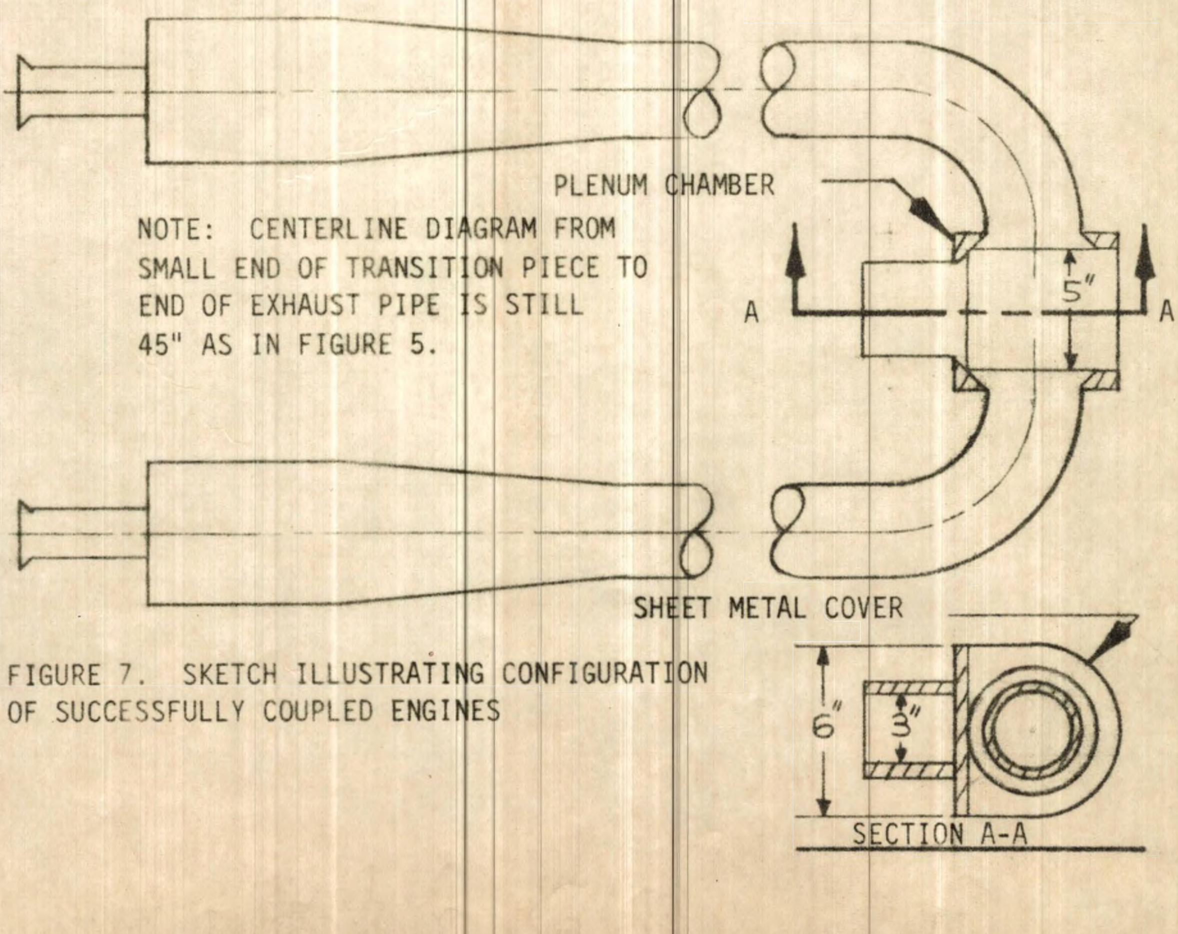


FIGURE 7. SKETCH ILLUSTRATING CONFIGURATION
OF SUCCESSFULLY COUPLED ENGINES

To achieve engine coupling through the exhaust pipes it was decided to attempt to use the pressure pulse from compression wave A of engine number 1 to reinforce compression wave D in engine number 2 and vice-versa. This would have the effect of timing the engines so that they fire alternately as desired. If the rarefaction waves could be made to interact similarly, the intake process could be prolonged, thus the volumetric efficiency improved. However, in this first attempt at coupling, only the compression waves were given consideration.

To implement the coupling, the engines were arranged as shown in figure 7. This arrangement is similar to Esnault-Pelterie's coupling of valved pulse jets. Notice, however, that with the current design, all thrusts (intakes plus exhaust) are in the same direction and, hence, all of the thrust produced can be utilized. This fact gives the coupled engines an advantage over Engebretson's single engine in that with Engebretson's engine, these thrusts were perpendicular. However, the propulsion efficiency of the coupled engines will likely be less than that of a single engine since the backflow in an exhaust pipe will now consist mainly of exhaust gases from the other engine which are less dense than the surrounding atmosphere.

With this design, the engines were found to fire alternately as desired. One could probably improve performance of the engines by using a nozzle as the outlet from the plenum chamber instead of a straight piece of pipe. However, it was felt that matching a nozzle to the rest of the engine assembly was beyond the scope of the thesis project, hence the straight pipe was used to study engine coupling without involving nozzle effects.

The gap between the ends of the two exhaust pipes was found to be not at all critical and a value of 5 inches was chosen for convenience of constructing the plenum chamber.

It was found that the stability of the engines was improved by shortening the intake pipes from 11.25" to 9" and, hence, the shortened pipes were used throughout the remainder of the experiment. The fact that stability was improved by shortening the intakes can be explained as follows: The frequency of the engine is directly proportional to the speed of sound (38). When the engines are coupled, the backflow down the tailpipe will be hot exhaust gases instead of fresh air and, hence, the average tailpipe temperature will increase. Since the speed of sound is proportional to the square root of the absolute temperature, the speed of sound will increase, thus increasing the frequency of the engines. It is thought that the intake acts primarily as a timing device and, hence, at the increased frequency, the intake must be shorter to permit the required flow in a decreased time. The increase in frequency has been verified experimentally, as described in Chapter 4.

CHAPTER IV

LABORATORY TECHNIQUES AND EXPERIMENTAL PROCEDURES

The data taken during this project may be divided into two classifications - primary data and supporting data. Data considered to be primary are those measurements which could be utilized directly in drawing the conclusions to be presented in Chapter 5. Specifically, the items of primary data are:

1. Thrust measurements.
2. Fuel flow measurements.
3. Proof that the engines were in phase opposition.

Data classified as supporting data are those measurements which serve to:

1. Support the primary data.
2. Monitor the engine performance for any unusual behavior.
3. Insure safe working conditions in the laboratory.

Specific items of supporting data are:

1. Average static pressure at the combustion chamber.
2. Frequency of operation of the coupled engines.
3. Frequency of operation of a single engine.
4. Noise levels for both single engine operation and coupled operation.
5. Carbon monoxide level in the laboratory.

The apparatus and methods used in collecting the data are described in the following paragraphs, with primary data being considered first.

When Engebretson performed his investigation, data were taken during the summer months and, hence, the engine could be run outdoors.

However, the timing of the current project was such that the data were to be taken during the winter and, therefore, an exhaust system to permit running the engine indoors had to be constructed. The design of this system is outlined in Appendix 2.

Also, an engine mounting device had to be provided which would allow the thrust to be measured. Such a device already existed from Engebretson's project and, rather than build an entirely new structure, Engebretson's device was modified to accept two engines instead of one. The modified mounting system with the coupled engines in position is shown in figure 8. The rack in which the engines were mounted was free to move as a parallelogram. With this design, the rack remains parallel to the level surface at all times. By using a balance system, the thrust produced is equal to the weight required to bring the rack back to the zero position. Friction effects may be considered negligible because the rack moves very freely with the use of ball bearings at the eight pivot points (39).

With the engines mounted as shown in figure 8, the thrust measured would be the sum of intake plus exhaust thrust. By rotating the plenum chamber 180 degrees as shown in figure 9, the difference between the intake and exhaust thrusts (intake thrust was greater) could be measured. Then, by solving two simultaneous algebraic equations, the individual thrusts (intake and exhaust) could be computed.

Propane was chosen as the fuel for the engine. This choice was made to keep the fuel the same as Engebretson's and also for laboratory convenience. However, it was found that one 100-lb. (the largest available) tank of propane was incapable of supplying fuel to the engines at the desired rate. Consequently, two tanks feeding into a common manifold were used to supply the engines. Also, a means had to be provided for switching the starting air and spark plug power supply from one engine to the other. The schematic apparatus arrangement is

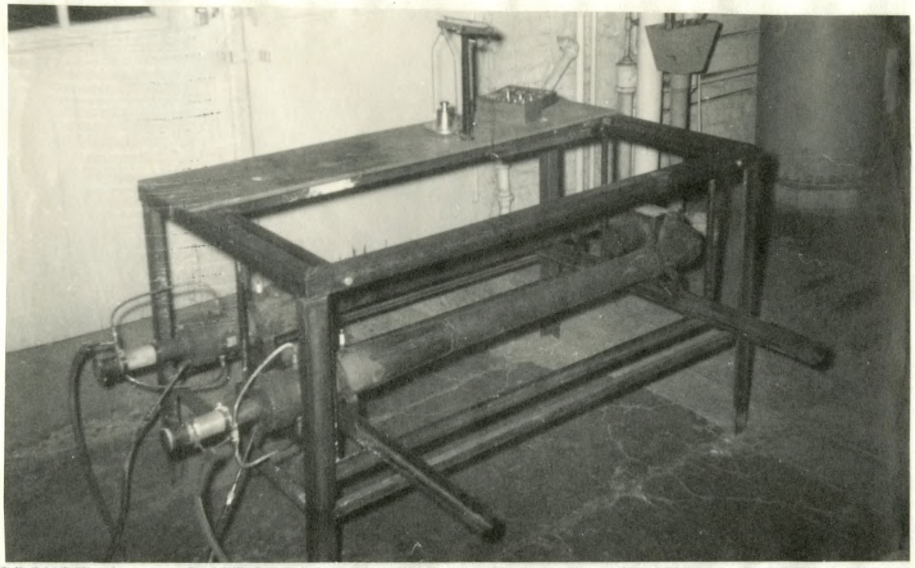


FIGURE 8a - PHOTOGRAPH SHOWING ENGINE MOUNTING DEVICE WITH ENGINES IN POSITION.

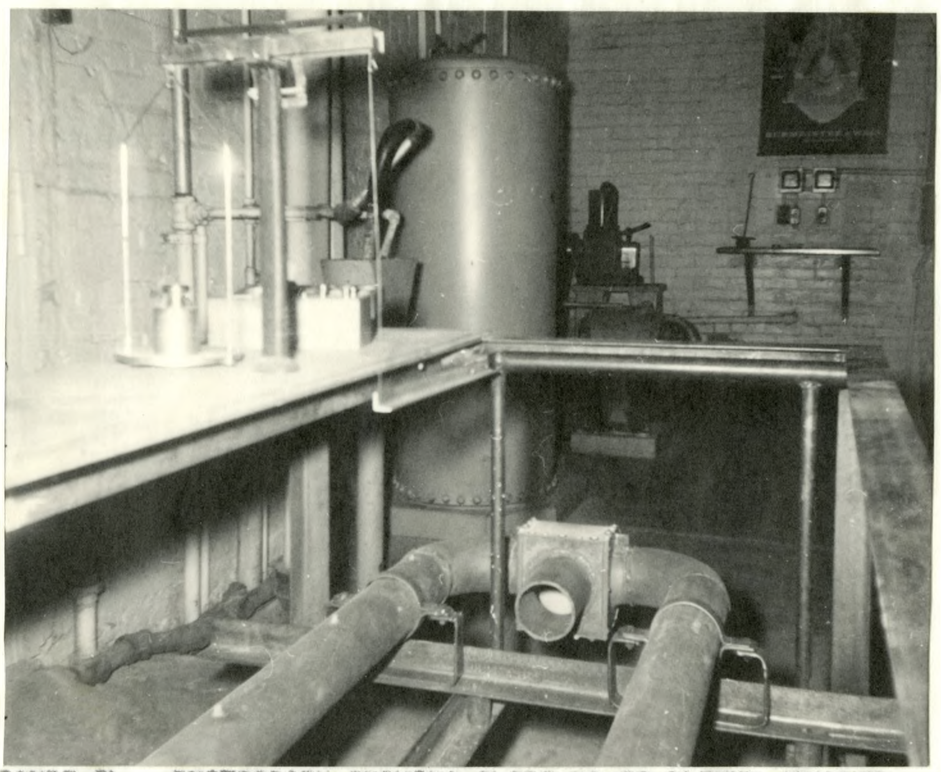


FIGURE 8b - PHOTOGRAPH SHOWING CLOSE UP OF PLENUM CHAMBER

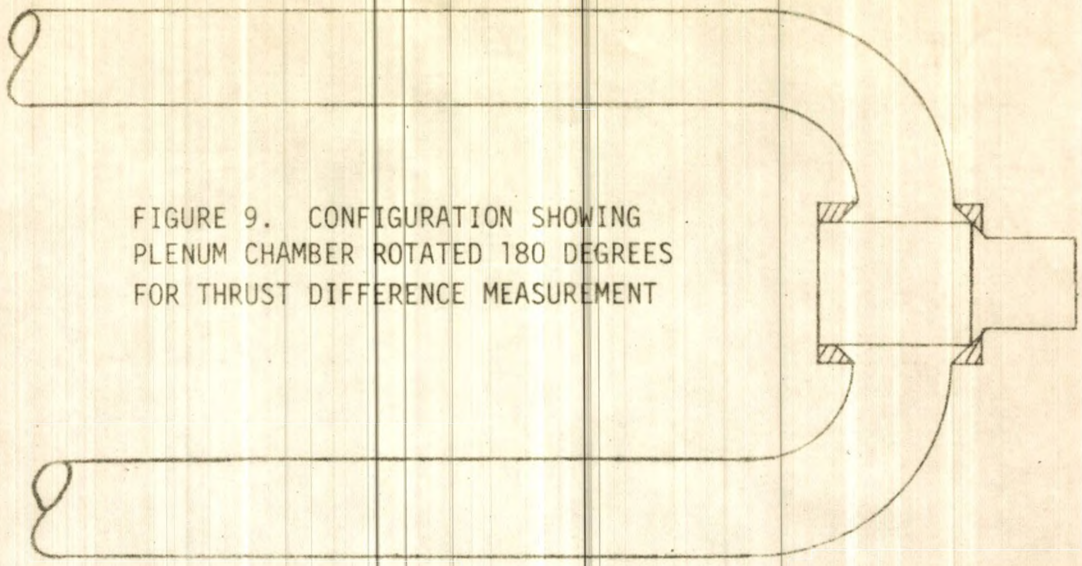


FIGURE 9. CONFIGURATION SHOWING PLENUM CHAMBER ROTATED 180 DEGREES FOR THRUST DIFFERENCE MEASUREMENT

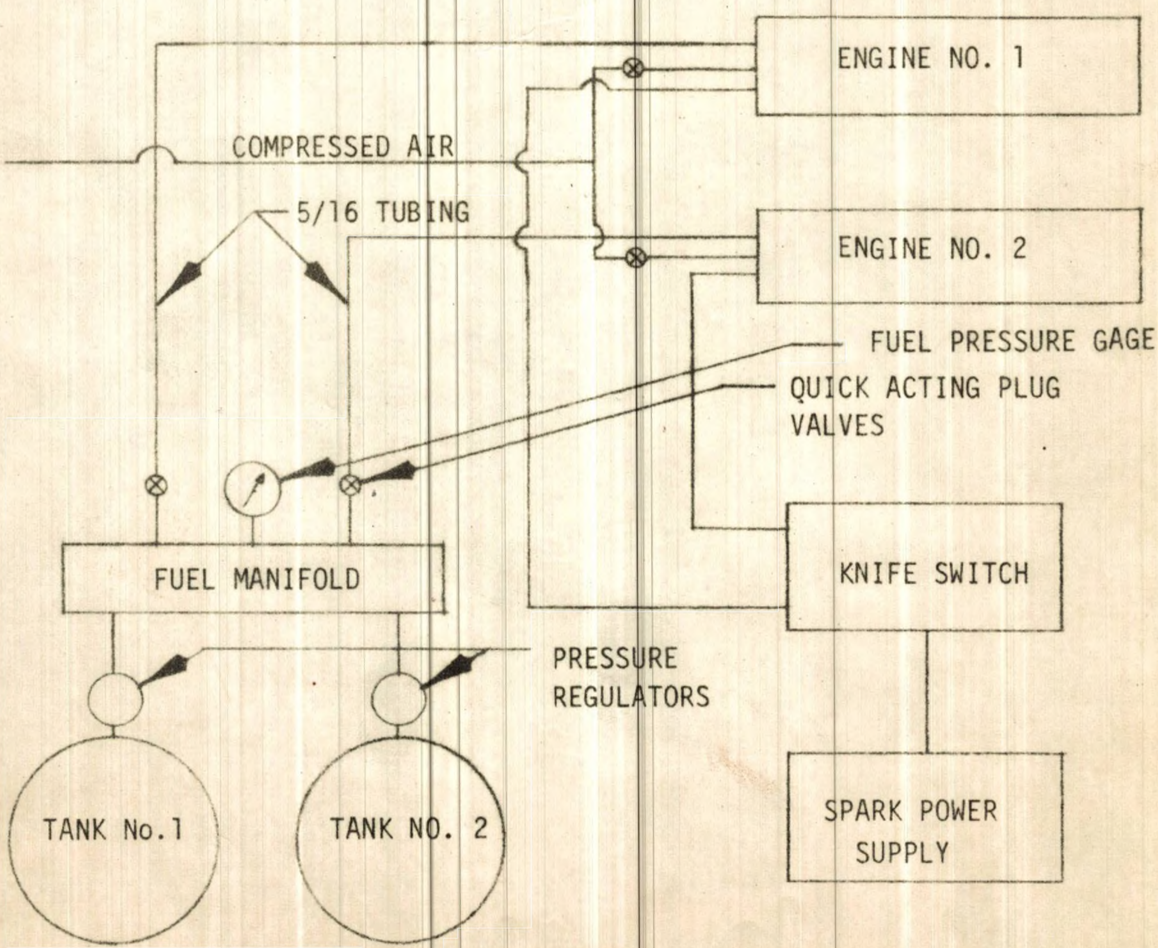


FIGURE 10. BLOCK DIAGRAM OF APPARATUS LAYOUT

shown in figure 10. Flexible lines were used to connect fuel and air lines to the engines so as not to interfere with thrust measurement.

All data were recorded as a function of fuel pressure measured at the manifold. The manifold was used to insure that the same fuel pressure was applied to each engine. Fuel pressure, however, was used as the independent variable merely for laboratory convenience since the more fundamental parameter of interest is fuel flow rate. Fuel flow rate as a function of fuel pressure was determined by placing the fuel tanks on a scale and recording the time required to consume a predetermined quantity of fuel. Thus, by plotting fuel flow calibration curves, data could be related to fuel flow rate as will be illustrated in Chapter 5.

Although the coupled engines ran satisfactorily, a means had to be devised to determine whether or not the engines were truly firing alternately. With the engines running, visible flames protrude from the intake pipes. By photographing the action of these flames with a Red Lake Laboratories "Hycam" high speed motion picture camera, it was definitely established, as described below, that the engines were in phase opposition (firing alternately).

To photograph the flames, the room was darkened and Kodak 4X (ASA 800) negative film was run at 1000 frames per second. However, the unaltered flame was not sufficiently bright to record on the film. Thus, a method was sought to brighten the flame. In the first attempt at brightening the flame, the apparatus described in Appendix 3 was used to inject sodium ethylate into the engines. It was thought that the sodium would ionize and burn to give the required brightness. Although the light meter reading could be increased from 3.5 to 5 with sodium ethylate, a minumum of light meter reading of 10 was required. As a second attempt at brightening, lignite coal dissolved in anthracine was injected into the engines. The lignite produced luminescent carbon particles and resulted in a flame brightness which was superior to that obtained from sodium ethylate but still not sufficient.

Successful brightening of the flames was finally achieved by burning a mixture of acetylene and propane. An acetylene tank was merely substituted for one of the propane tanks in the fuel system. With this arrangement, the engines were started on propane after which acetylene was blended in until sufficient brightness was obtained. An example of the high speed pictures is shown in figure 11. By studying figure 11, it can be seen that a sequence of flames appears to be issuing first from the right small dot and then from the left. The dots (called out by the white arrows) are marker lights positioned at the ends of the intake pipes. Thus, the figure shows the flame protruding first from the right engine and then from the left engine. Although figure 11 displays only two cycles of operation, the entire 100-foot roll of film showed the same pattern of firing and, thus, verified the assumption that the engines were in phase opposition.

As supporting evidence, the beats described in Chapter 3 were no longer present. Other supporting data were collected using the techniques described below.

The operational frequency of the engines was measured using a General Radio type 760 sound analyzer; the noise level in the vicinity of the operating engines was measured with a General Radio type 1555A sound survey meter. The noise level at a location approximately 3 feet from the exhaust pipe of the nearest engine ranged from 124 to 131 decibels. It was necessary to wear ear protectors at all times while working in the same room with the operating engines.

Engebretson found that the average static pressure readings varied with the type of manometer used and also with the length of the

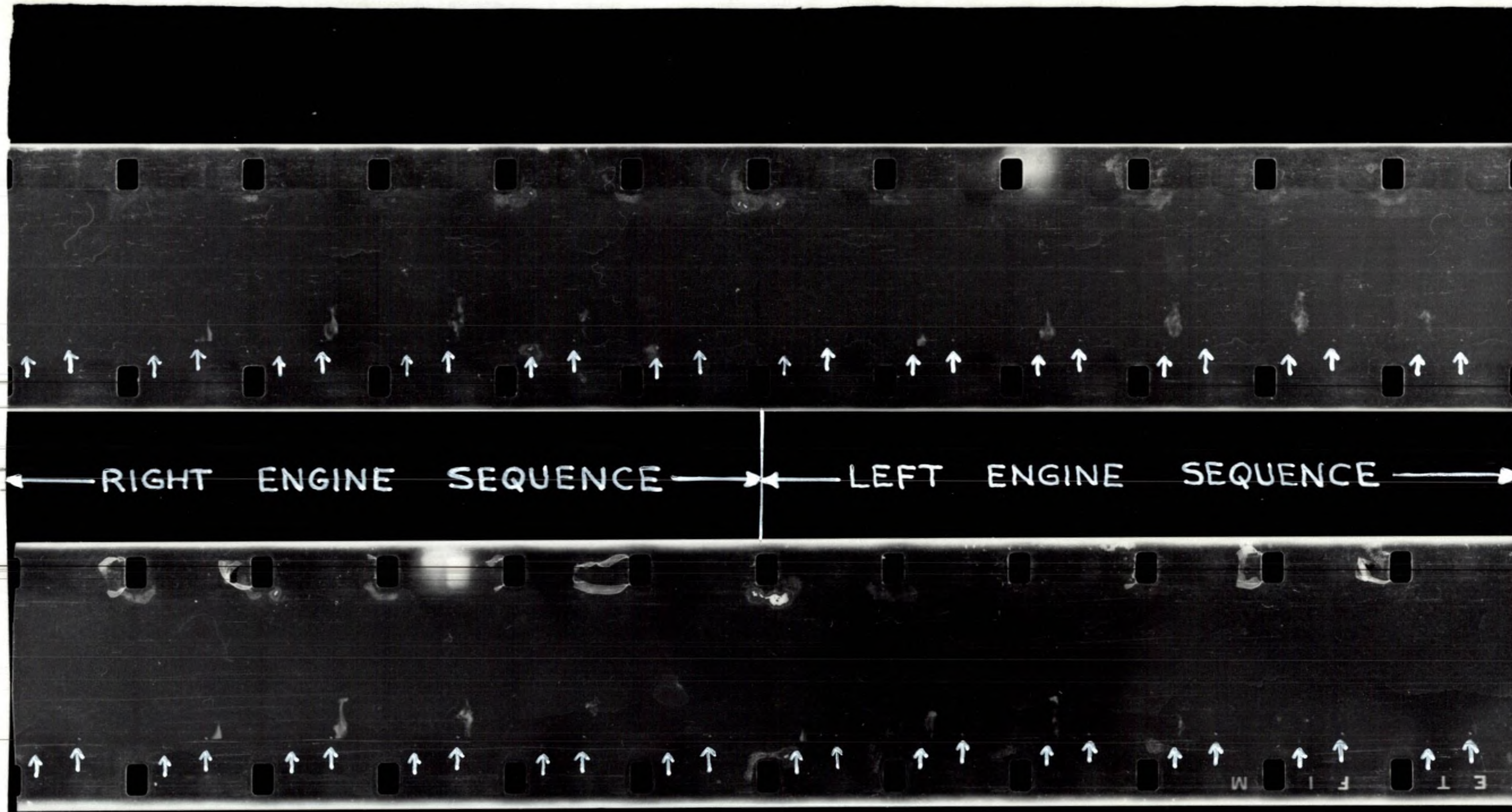


FIGURE 11. HIGH SPEED PHOTOGRAPHS

connecting line (40). Hence, no attempt was made to measure the true average static pressure in the engines. However, a U-tube water manometer was connected to the combustion chambers and the resulting readings were found useful in a qualitative manner, as described in Chapter 5.

The carbon monoxide level in the laboratory was monitored using both a Mine Safety Appliance #DS-47133 carbon monoxide tester and several of the Bendix card type carbon monoxide detectors intended for use in light aircraft. In general, carbon monoxide presented no major problem - maximum carbon monoxide level being approximately 0.0025 per cent.

The results and conclusions from the above data are presented in Chapter 5.

CHAPTER V

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

In keeping with the objectives of the project, two valveless pulse jet engines have been operated successfully in phase opposition. However, the coupling of the engines seems to have caused deterioration in the performance rather than improvement. Some benefits, though, were realized from coupling and it is thought that the coupled engine's performance can be improved through further research. Coupled engine performance is discussed in the following paragraphs in terms of:

1. Thrust and fuel consumption.
2. Noise level.
3. Thrust specific fuel consumption.
4. Observed phenomena which are considered to warrant further investigation.

From figure 12 it can be seen that the maximum thrust produced was 5.85 lb_f at a fuel rate of 29.5 lb_m/ hour / engine. Engebretson's maximum single engine thrust was 6.0 lb_f at a fuel rate of 24.5 lb_m per hour. Notice that, with the coupled engines, it was possible to run at higher fuel rates. In fact, for the coupled engines, the maximum fuel rate was dictated by the capacity of the fuel system rather than the rich stability limit of the engines. To get a better thrust comparison between the coupled engines and Engebretson's engine, consider a fuel rate of 24 lb_m / hour / engine. The coupled engines produced a thrust of 5.58 lb_f (2.79 lb_f per engine) while Engebretson's single engine produced 5.9 lb_f thrust. However, Engebretson's intake thrust was at

THRUST VERUS FUEL CONSUMPTION

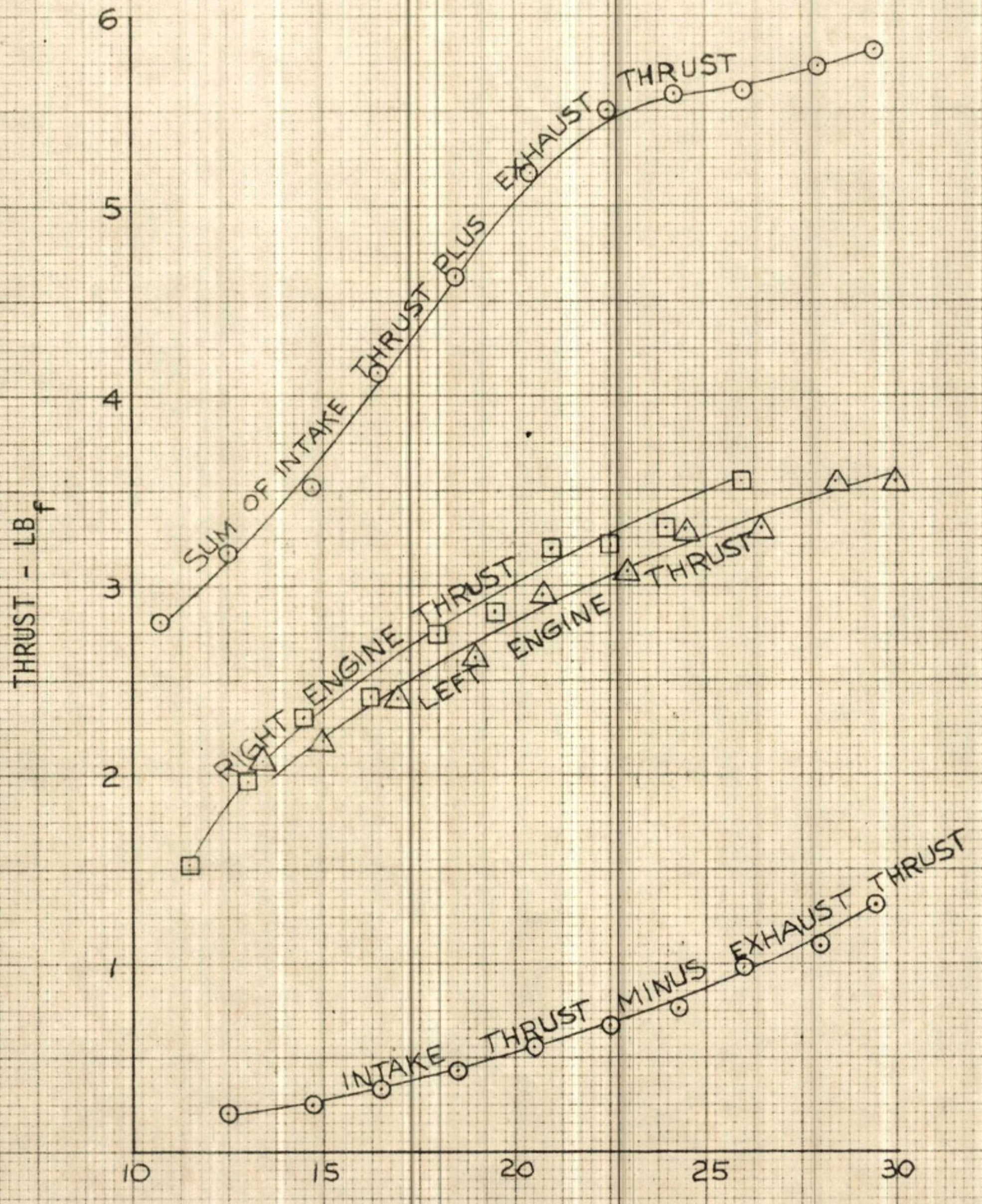


FIGURE 12

90 degrees to the exhaust thrust so that his recoverable thrust might be considered to be the exhaust thrust of 3.88 lb_f. Still, one must conclude that the performance of the coupled engines was definitely inferior. At a fuel rate below the step in the thrust curve, the coupled engines compare more favorably but are still inferior.

However, notice that the single engine thrusts from figure 12 are also well below Engebretson's values. This decrease may be an inherent fault of the present configuration but, on the other hand, the fact that the right engine produced a slightly higher thrust than the left indicates that the single engine thrusts may be sensitive to careful fine tuning. This idea is reinforced by Engebretson's experience. His relatively high thrust values resulted from an extensive fine tuning effort.

Suppose that, through fine tuning, the single engine thrusts could be made to approach Engrbretson's values. Then, even though the thrust of the coupled engines might not be double the single engine thrust, the recoverable thrust from the coupled engines might well be greater than double the single engine recoverable thrust.

Although this author is not yet ready to desert engine coupling, it does appear that it would be of interest to experiment with a U-shaped single engine such as the one depicted in figure 13. Since the valveless pulse jet seems to be insensitive to changes in the exhaust pipe configuration, it is thought that such an engine would likely run and would possibly produce a high recoverable thrust.

However, engine coupling is still attractive in that herein lies a potential for the two engines reinforcing one another and for noise cancellation. In this experiment the engines apparently did not reinforce but there did appear to be noise cancellation as was expected. The noise level at the operator's position ranged from 124 to 131

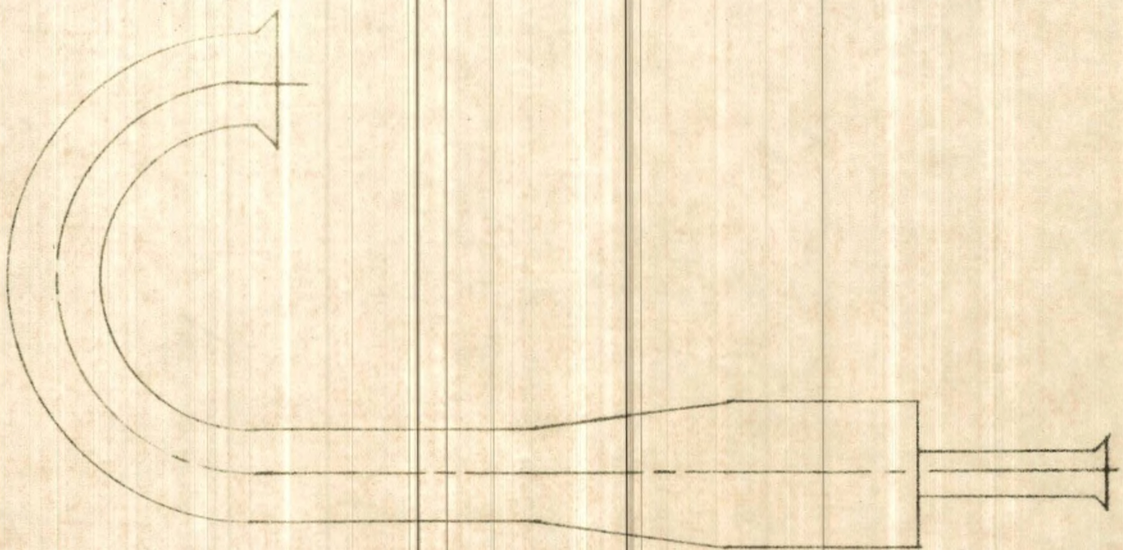


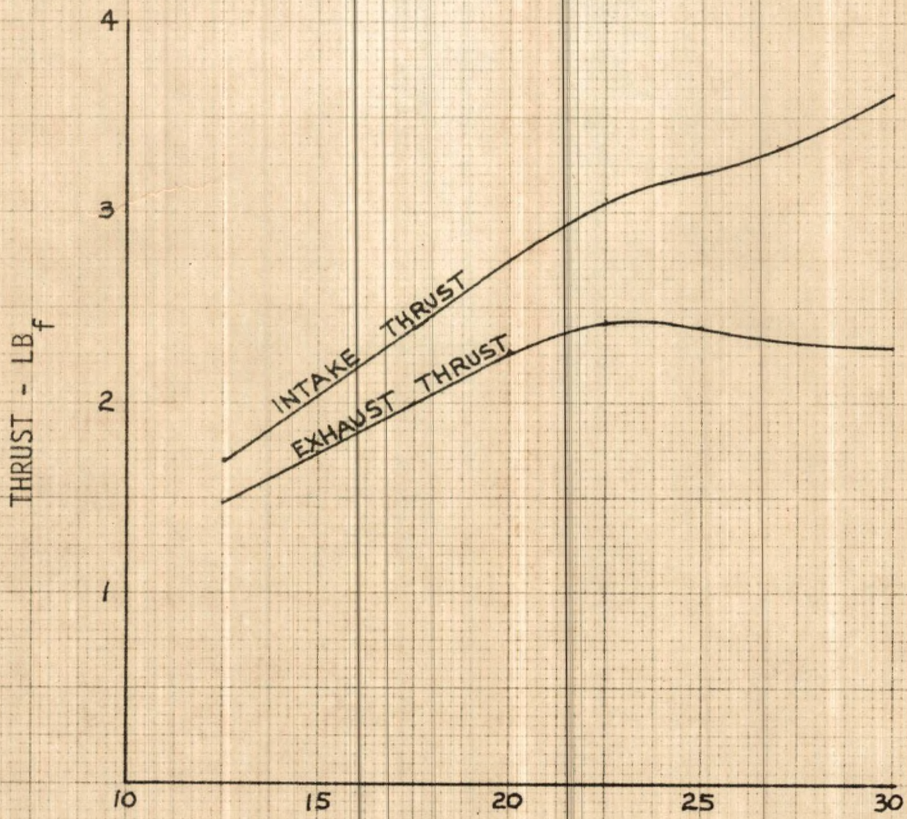
FIGURE 13. CONFIGURATION FOR PROPOSED INVESTIGATION

decibels but, for a given fuel rate per engine, the noise level was the same regardless of whether one or two engines were running. Thus, the coupling did result in an improved thrust / noise ratio. With both engines running, the frequency of operation increased from nominally 100 cps to nominally 104 cps. This increase was expected on the basis of the increase in average exhaust pipe temperature.

On examining the total thrust curve of figure 12, one notices a peculiar step in the curve at approximately 25 lb_m / hour / engine. This step was at first viewed with suspicion but a complete rerun of the data confirmed the curve. More light is thrown on the situation when one computes the individual intake and exhaust thrusts. From figure 14 it can be seen that although the intake thrust continues to increase with increasing fuel rate, the exhaust thrust actually reaches a maximum at approximately 24 to 25 lb_m / hour / engine. Notice also that from figure 15, the average static pressure at the combustion chamber increased noticeably at this fuel rate. This rise was not present in any of the single engine pressure measurements. It is quite evident that some phenomenon is occurring at approximately 25 lb_m / hour / engine which causes a change in the mode of operation of the engines.

Although detailed investigation of the above phenomenon was considered to be beyond the scope of this project, it is here postulated that the phenomenon is a choking effect at the plenum chamber outlet. This effect would be analogous to the choking which occurs when sonic velocity is reached at the throat of a steady flow nozzle. However, since the flow from the plenum chamber is unsteady, the problem is more complicated. It is suggested that investigation of the phenomenon be the topic of a future research project. Such a project might incorporate investigation of a nozzle outlet for the plenum chamber and the effects of plenum chamber dimensions.

INDIVIDUAL THRUSTS VERSUS FUEL CONSUMPTION



FUEL FLOW - LB_m/HR PER ENGINE

FIGURE 14

COMBUSTION CHAMBER

AVERAGE STATIC PRESSURE VERSUS FUEL CONSUMPTION

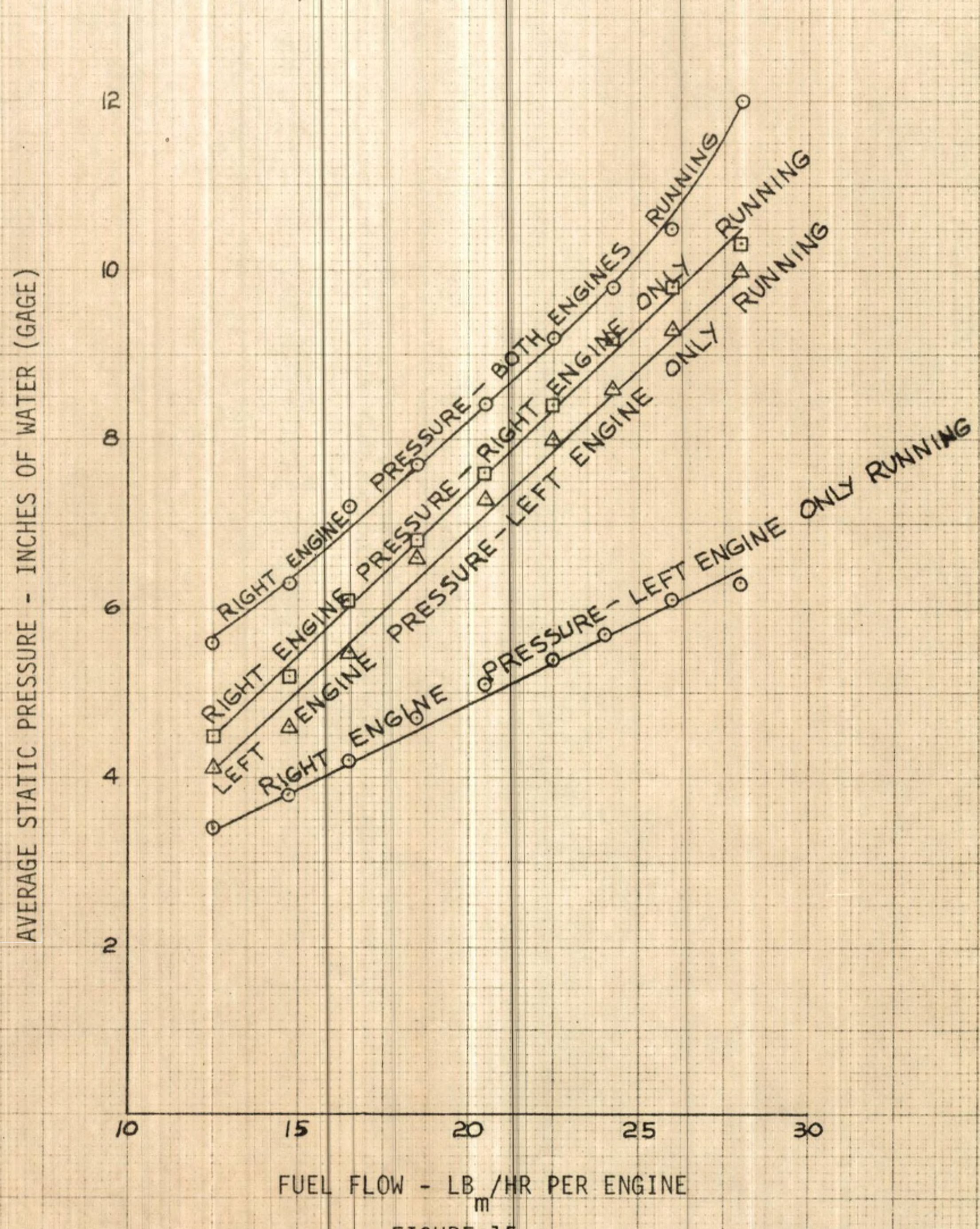


FIGURE 15

From figure 16, notice that fuel flow calibration curves had to be drawn for each individual engine as well as for both engines. Not only are the curves for the individual engines different but, at a given fuel pressure, the sum of the single engine fuel flows is, in general, greater than the fuel flow with both engines running. Figure 16, however, correlates with figures 14 and 15.

From figure 14, notice that, at the same fuel rate, the left engine consistently produced less thrust than the right engine. Correlating figure 14 and 15, it is felt that the reduced thrust from the left engine resulted from the reduced average static pressure. It is thought that the increased fuel flow to the left engine (see figure 16) also resulted from the decreased average static pressure, which produced a greater average pressure difference across a given length of fuel line. Thus, there appears to be some small difference between the two engines which gave the right engine a superior ability to convert the energy of the fuel into pressure and, hence, thrust. It is felt that any effort to fine tune the existing engines should be aimed at producing the maximum average static pressure for a given fuel rate.

Figure 17 shows the thrust specific fuel consumption of the coupled engines. The thrust specific fuel consumption was computed by dividing the fuel rate by the thrust and, in all cases, the figures are too high to be of practical value. These figures compare rather unfavorably with the values of $1.2 \frac{lb_f}{hr\text{-}lb_m}$ reported by the French (41).

When attempting to brighten the protruding flames for photography by injecting sodium ethylate, a very interesting sideline observation was made. It was observed that the engine would accept much more sodium ethylate if the injection was axially through the valve end of the pulse jet tube rather than radially through the sidewall of the combustion chamber. In eithercase, large amounts of sodium ethylate would cause the engines to stop. However, where attempting to inject

FUEL FLOW CALIBRATION CURVES

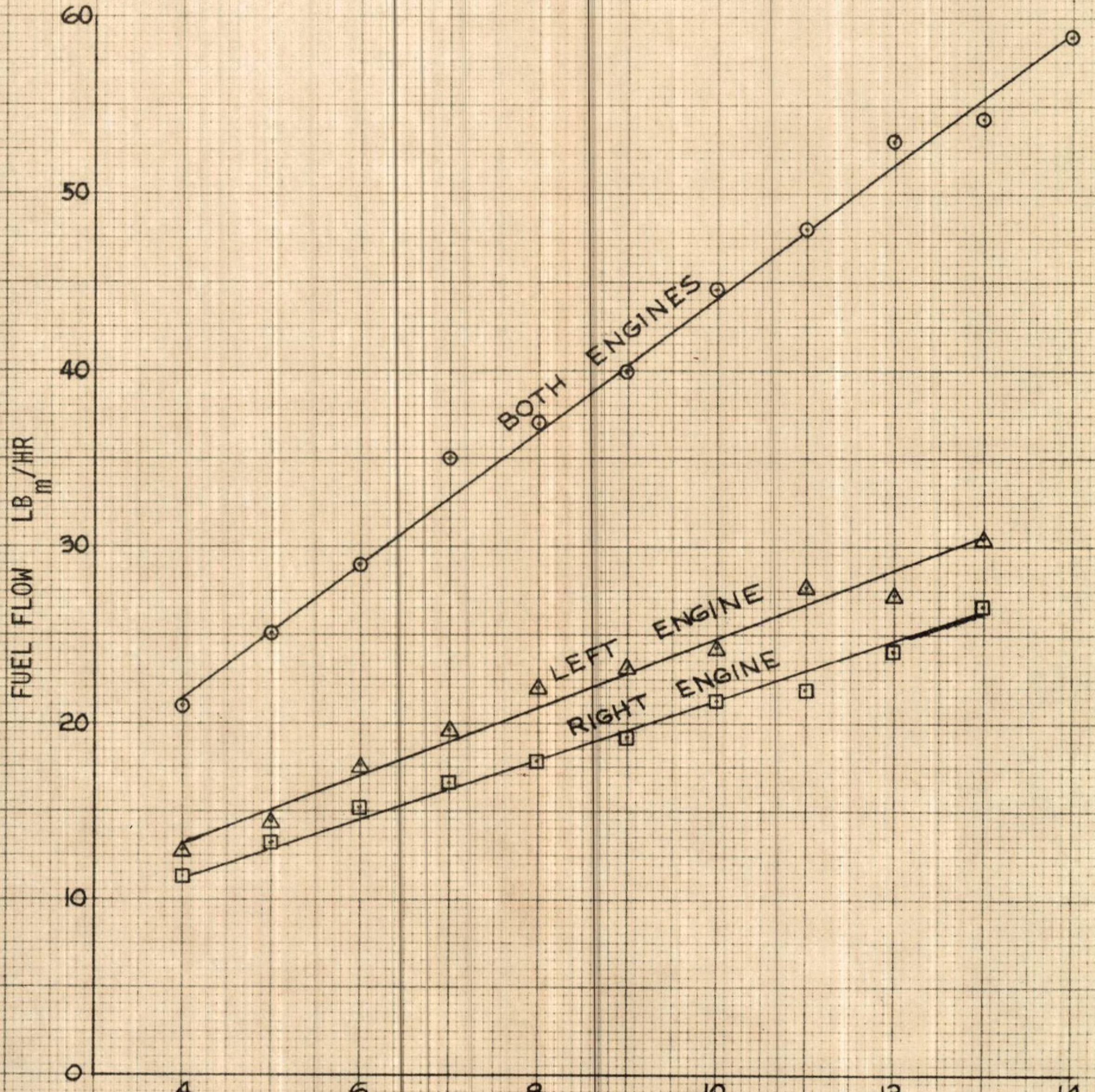


FIGURE 16

THRUST SPECIFIC FUEL CONSUMPTION VERSUS FUEL FLOW

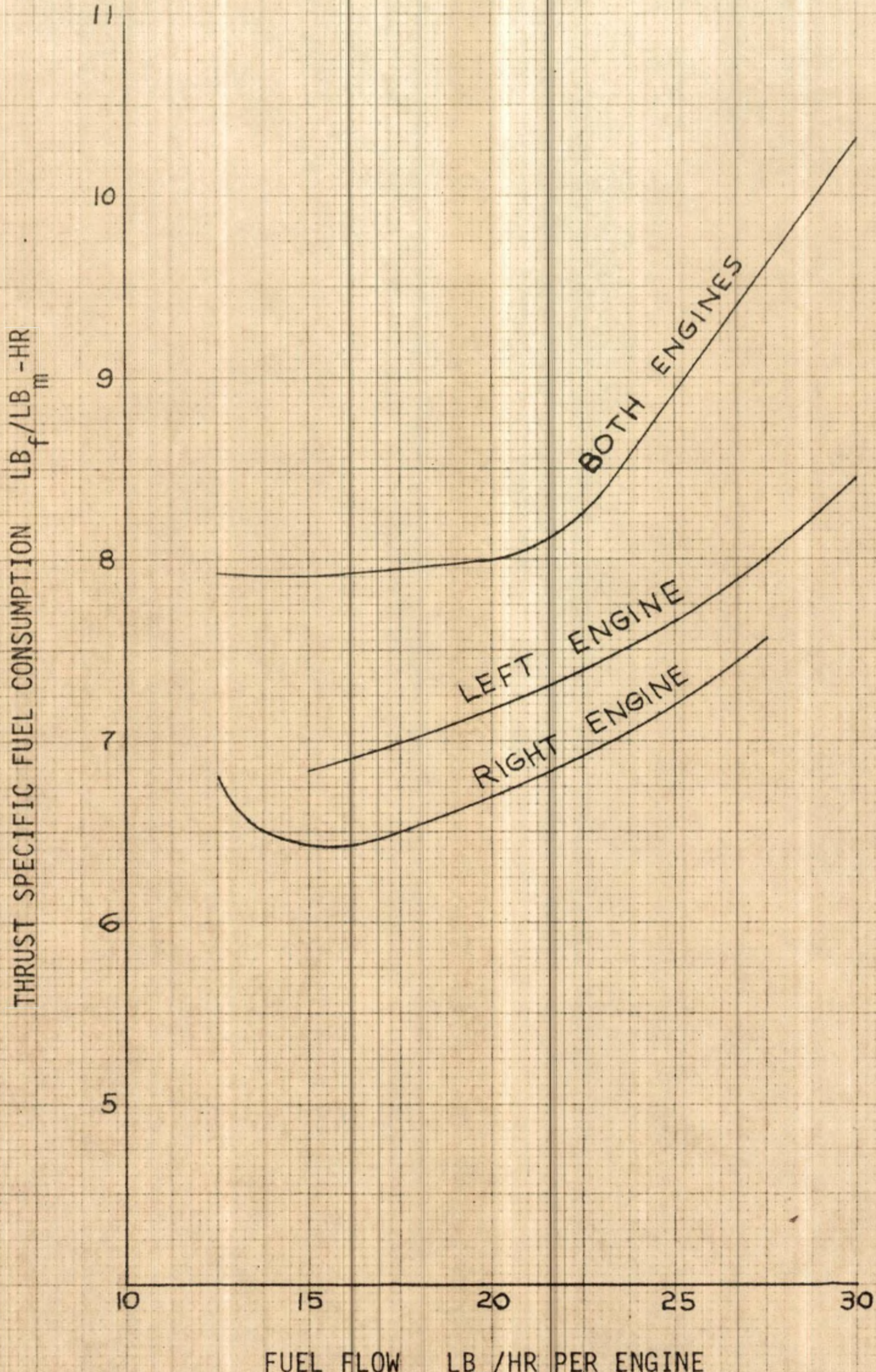


FIGURE 17

radially, any amount beyond a mere trace (quantitative measurements were not taken here since the objective was merely to brighten the flame) would cause the engines to stop. Since significantly larger amounts of the liquid could be injected axially without adverse effects, it was obviously not just the presence of sodium ethylate which caused the engines to stop. A more complex phenomenon must be involved.

Since this phenomenon was merely a sideline observation, it was not pursued in detail. The best explanation this author can give is that the radial injection caused an adverse reaction with the internal boundary layer - possibly causing it to change prematurely from laminar to turbulent flow. If such is the case, the observed phenomenon supports the reignition theory of Reynst which says that reignition is caused by ignition nuclei in the boundary layer. Reignition then occurs when the intake flow ceases to be laminar and becomes turbulent so that the ignition nuclei are transported into the charge (42).

Although the performance of the coupled engines was inferior to Engebretson's single engine performance, some benefits were realized and it is thought that there is a potential for improvement through further research. Suggested projects are:

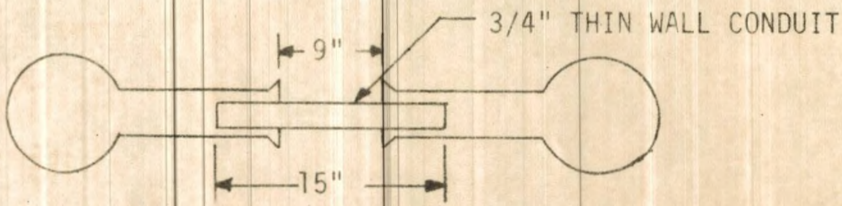
1. Investigate fine tuning of the engines.
2. Investigate the choking phenomenon observed and in conjunction, investigate the effect of plenum chamber configuration and nozzle outlet.
3. Investigate the nature of flow in the intakes.
4. Investigate a U-shaped single engine.
5. Investigate coupling the engines by getting rarefaction waves to reinforce.
6. Investigate in detail the mechanism of reignition.

However, if the maximum contribution is to be made, a really fundamental study of the valveless pulse jet should be made. Such a project would require more laboratory equipment than was available at the start of this investigation. The high speed camera which became available during the investigation may well open new avenues of research (43).

APPENDIX 1

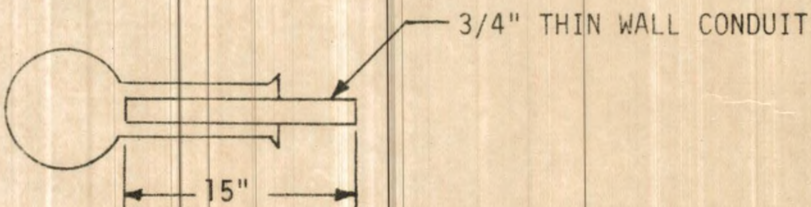
GEOMETRIC SHAPES TRIED IN INTAKE COUPLING

TRIAL 1:



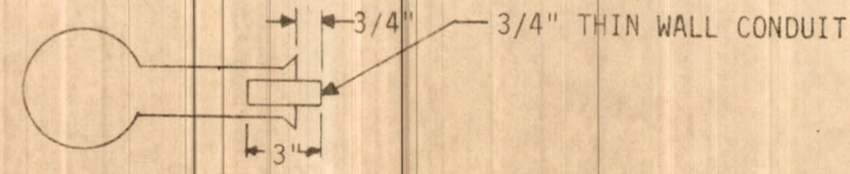
With this arrangement, the center tube was to transfer the central core of exhaust without interfering with the intake. The scheme failed. The engines would start but would not run with the starting air turned off.

TRIAL 2:



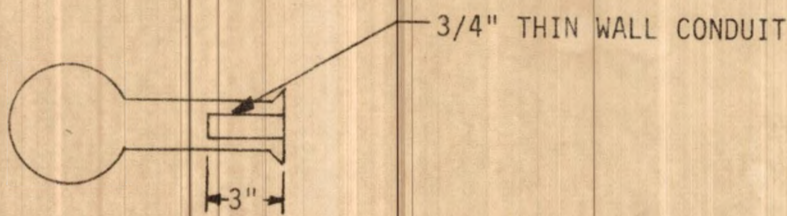
Trials 2 through 11 were performed to "feel out" what types of shapes, if any, the engines would accept. Here, as in trial 1, engine operation was not possible with the starting air off.

TRIAL 3:



Satisfactory operation was possible over a limited range of fuel pressure from 2 to 4 psig.

TRIAL 4:

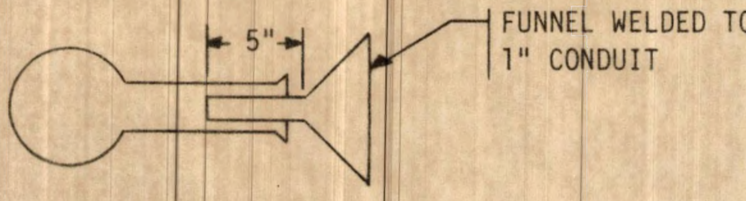


Satisfactory operation was possible over a limited range of fuel pressure from 2 to 4 psig.

TRIALS 5, 6, 7, AND 8:

In trials 5, 6, 7, and 8, the length of the conduit, L, was made equal to 3, 4, 5, and 6 inches respectively. With L equal to 3 inches, satisfactory operation was possible over a limited range of fuel pressure from 2 to 4 psig. With L equal to 4 inches, the maximum attainable fuel pressure increased to 5 psig but dropped back to 4 psig when L was made equal to 5 inches. If the fuel pressure was increased to above these levels, the engines simply stopped. When L was increased to 6 inches, engine operation was not possible with starting air off.

TRIAL 9:

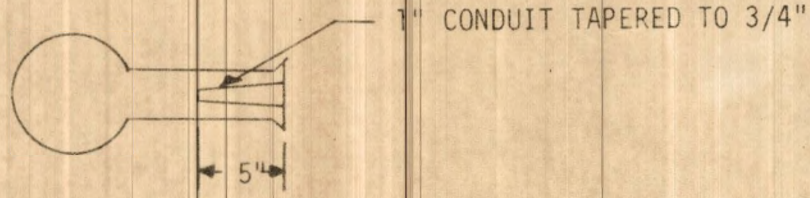


Satisfactory operation was possible over a limited range of fuel pressure from 2 to 5 psig.

TRIAL 10:

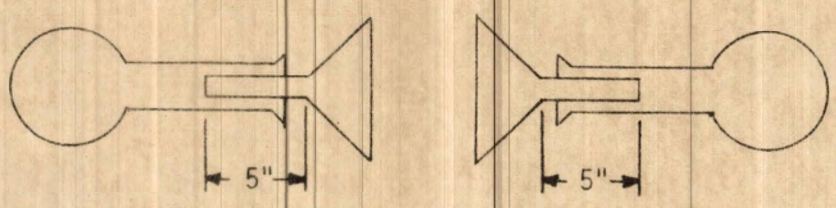
Engine operation was not possible with starting air off.

TRIAL 11:



Engine operation was possible but marginal.

TRIAL 12:



In this trial, both engines were equipped with the funnels of trial 9. The funnels were to transfer the exhaust without interfering with the intake. Engine operation was possible over a limited fuel pressure range, but coupling did not result.

APPENDIX 2

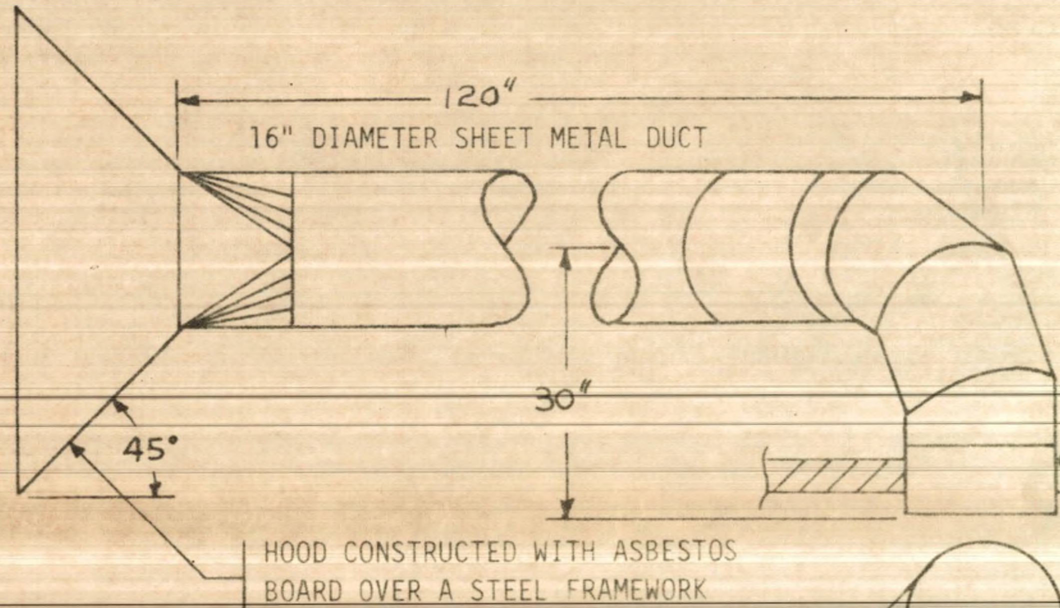
DESIGN OF THE LABORATORY EXHAUST SYSTEM

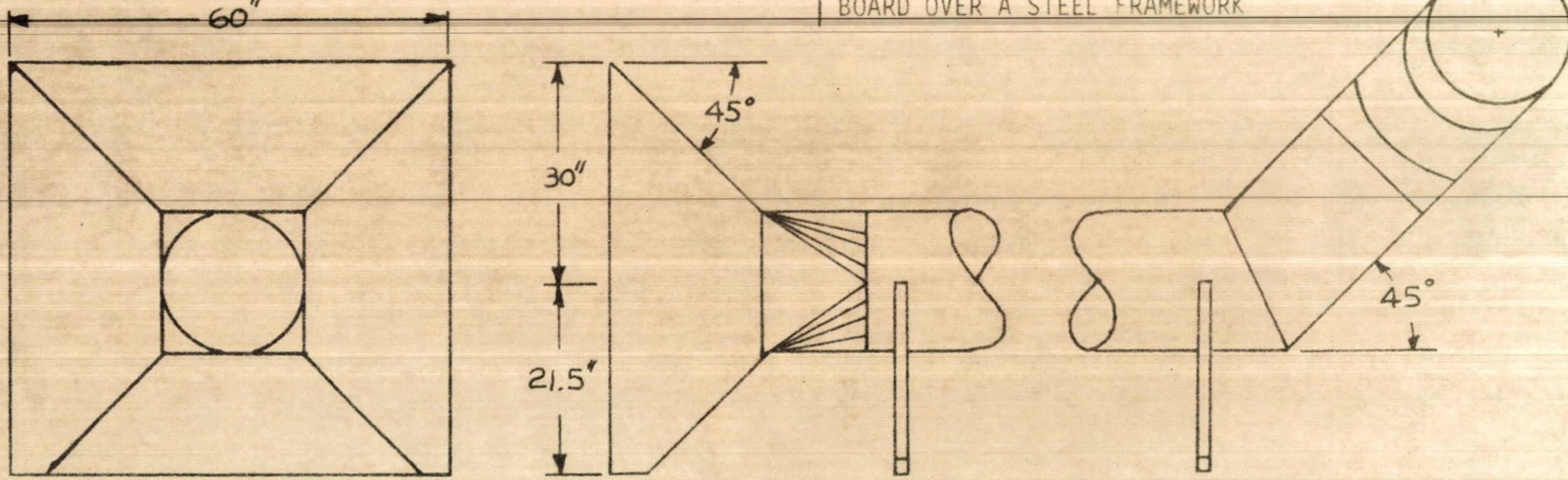
The internal combustion engine laboratory, located in Chandler Hall on the University of North Dakota campus, made an ideal location for running the valveless pulse jet engines indoors. This laboratory is equipped with a 60-foot chimney which made an excellent exit into which the exhaust gases could be channeled. It was only necessary to construct a hood to collect the gases and a duct to convey them into a clean-out door near the base of the chimney. The natural draft of the chimney was sufficient to provide the required pressure difference across the duct so that no exhaust fan was necessary. A sketch of the hood and duct arrangement is shown in figure 18.

For convenience of construction, it was found desirable to use a duct of circular cross section limited to 16 inches in diameter. Before proceeding with the construction, however, it was necessary to estimate whether or not the 16 inch diameter duct would allow the use of only natural draft. Using Engebretson's performance data, it was estimated that 3080 CFM should be removed. Then, using methods described in reference 44, it was estimated that a pressure difference across the duct of 0.15 inches of water was required. A manometer connected between the chimney and the room showed that on the average, a differential of approximately 0.12 inches of water was available. Thus, the 16 inch diameter duct appeared marginal.

However, the duct construction proceeded with the idea that some sort of exhaust fan could be provided if necessary. No fan was necessary. The duct provided adequate ventilation for all configurations except the arrangement shown in figure 9 (page 14). With this configuration, the intake pipes were pointed away from the hood and it was necessary to wear a gas mask while collecting data. Fortunately, only a limited amount of data were required from this arrangement.

FIGURE 18. SKETCH OF LABORATORY EXHAUST SYSTEM





APPENDIX 3

APPARATUS FOR INJECTION OF LIQUIDS INTO THE VALVELESS PULSE JET ENGINES

A sketch of the injection apparatus is shown in figure 19. The pressure vessel was fashioned from a piece of 3-inch steel pipe and was pressurized (air over liquid) to approximately 20 psig. Liquid flow to the engines was then controlled with the needle valves.

A previous version of the apparatus attempted to control the feed of liquid by manually pressurizing the vessel with a bicycle pump. The resulting feed, however, was too unsteady and this scheme was abandoned in favor of the apparatus of figure 19.

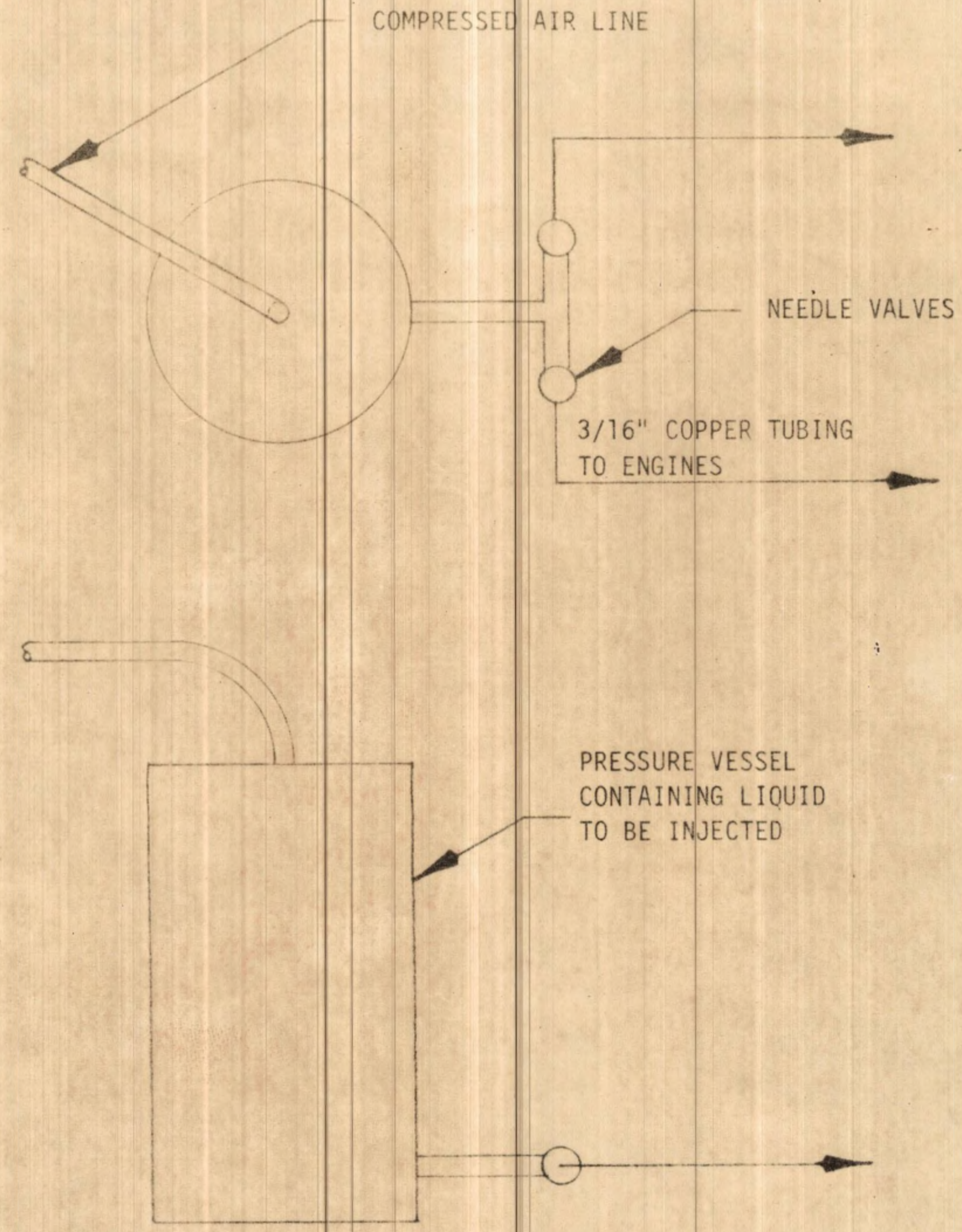


FIGURE 19. SKETCH OF INJECTION APPARATUS

APPENDIX 4

PERFORMANCE DATA

COUPLED ENGINE PERFORMANCE DATA

FUEL FLOW lb_m/hr	TOTAL THRUST lb_f	INTAKE THRUST MINUS EXHAUST THRUST lb_f	FREQUENCY cps	NOISE LEVEL db
21.5	2.82	-	104	124
25.0	3.18	0.22	105	127
29.5	3.53	0.265	105	125
33.0	4.19	0.331	105	127
37.0	4.64	0.441	105	128
41.0	5.18	0.551	105	128
45.0	5.51	0.661	104	129
48.5	5.62	0.771	103	130
52.5	5.62	0.985	104	130
56.0	5.74	1.10	104	130
59.0	5.84	1.32	105	131

COMPUTATION OF INTAKE AND EXHAUST THRUSTS

FUEL FLOW lb_m/hr	I + E lb_f	I - E lb_f	I lb_f	E lb_f
12.5	3.16	0.22	1.69	1.47
15.0	3.78	0.30	2.04	1.74
17.5	4.40	0.40	2.40	2.00
20.0	5.00	0.50	2.75	2.25
22.5	5.50	0.65	3.07	2.43
25.0	5.60	0.82	3.21	2.39
27.5	5.70	1.05	3.37	2.33
30.0	5.90	1.35	3.62	2.28

APPENDIX 4

PERFORMANCE DATA

COUPLED ENGINE PERFORMANCE DATA

FUEL FLOW lb_m/hr	TOTAL THRUST lb_f	INTAKE THRUST MINUS EXHAUST THRUST lb_f	FREQUENCY cps	NOISE LEVEL db
21.5	2.82	-	104	124
25.0	3.18	0.22	105	127
29.5	3.53	0.265	105	125
33.0	4.19	0.331	105	127
37.0	4.64	0.441	105	128
41.0	5.18	0.551	105	128
45.0	5.51	0.661	104	129
48.5	5.62	0.771	103	130
52.5	5.62	0.985	104	130
56.0	5.74	1.10	104	130
59.0	5.84	1.32	105	131

COMPUTATION OF INTAKE AND EXHAUST THRUSTS

FUEL FLOW lb_m/hr	I + E lb_f	I - E lb_f	I lb_f	E lb_f
12.5	3.16	0.22	1.69	1.47
15.0	3.78	0.30	2.04	1.74
17.5	4.40	0.40	2.40	2.00
20.0	5.00	0.50	2.75	2.25
22.5	5.50	0.65	3.07	2.43
25.0	5.60	0.82	3.21	2.39
27.5	5.70	1.05	3.37	2.33
30.0	5.90	1.35	3.62	2.28

LEFT ENGINE PERFORMANCE DATA

FUEL FLOW lb_m/hr	THRUST lb_f	FREQUENCY cps	NOISE LEVEL db
13.5	2.09	-	-
15.0	2.20	99	127
17.0	2.42	-	-
19.0	2.64	99	128
20.8	2.98	-	-
23.0	3.09	99	129
24.5	3.31	-	-
26.5	3.31	100	130
28.4	3.52	-	-
30.0	3.53	99	130

RIGHT ENGINE PERFORMANCE DATA

FUEL FLOW lb_m/hr	THRUST lb_f	FREQUENCY cps	NOISE LEVEL db
11.5	1.55	99	124
13.0	1.98	-	-
14.5	2.32	99	126
16.2	2.42	-	-
18.0	2.76	100	128
19.5	2.87	-	-
21.0	3.20	100	128
22.6	3.20	-	-
24.0	3.31	101	131
26.0	3.53	-	-

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